guide, measurements made at a frequency of 3·3GHz [3] have suggested that the following should normally be regarded as opaque to microwaves:

(a) rows of trees in leaf, if more than two in depth;
(b) trunks of trees, whether leafless or in leaf;
(c) walls of masonry, if more than 20cm in thickness;
(d) any but the lightest wooden buildings, particularly if containing partitions.

In spite of these rather gloomy conclusions and their implications for propagation across an urban environment, it should be pointed out that in the author's experience 3·4GHz signals have been received through hedges and individual trees in leaf and in one case over a 1km path through a housing estate, the transmitting and receiving antennas being inside houses on opposite sides of a hill some 30m high. The lesson to be learned from this test is clear; even if on paper a particular path is not line of sight it is still possible, on occasion, to transmit signals over it, as other propagation effects such as diffraction, scattering or ducting may come to the rescue. Herein lies the challenge and fascination of amateur radio at microwave frequencies.

References

[1] "The radio refractive index gradient over the British Isles", by J. A. Lane. *J Atmos Terrestrial Phys*, 1961, Vol 21, pp 157–166.

[2] "Multiple knife-edge diffraction of microwaves", by J. Deygout. *IEEE Trans on Ant & Prop*, 1966, AP14, pp 480–489.

[3] "Some experiments on the propagation over land of radiation of 9·2cm wavelength, especially on the effect of obstacles", by J. M. McPetrie and L. H. Ford. *J IEE*, 1946, 93 IIIA, pp 531–538.

Appendix

Imperial Unit equivalents of equations (4)–(9)

$$h_{feet} = \frac{L^2}{1{\cdot}5K}, \text{ L in miles} \quad (4)$$

$$d \text{ miles} = 1{\cdot}22\sqrt{K\,h_{feet}} \quad (5)$$

$$L > 1{\cdot}22\sqrt{K(h_1 - h_3)} + 1{\cdot}22\sqrt{K(h_2 - h_3)} \quad (6)$$

L in miles; h_1, h_2, h_3 in feet

$$h_{feet} = \frac{d\,(L - d)}{1{\cdot}5K} \quad d, L \text{ in miles} \quad (7)$$

$$h_{feet} = \frac{d\,(L - d)}{1{\cdot}5K} + \frac{d\,(h_1 - h_2)}{L} \quad (8)$$

d, L in miles; h_1, h_2 in feet

$$S_{min}\,(\text{feet}) > 1369\sqrt{\frac{d_1 d_2}{(d_1 + d_2)\,f}} \quad (9)$$

d_1,d_2 in miles, f in megahertz

Some meteorological aspects of the anomalous propagation of radio waves

by E. R. Thomas*

RADIO transmissions within the vhf/uhf bands (30–3,000MHz) are often directional and line of sight so that the horizon is about the limit for useful transmissions. At these frequencies radio waves passing upwards through the atmosphere are lost into space; that is, they are not reflected by the ionosphere as are radio waves of lower frequency, and for this reason vhf/uhf transmissions are beamed more or less horizontally. Unlike longer waves the whole of the path length of vhf/uhf transmissions is in the troposphere, which is the layer of air extending from the earth's surface up to about 11km (35,000ft)—in European latitudes—and is the region within which clouds, rain and weather occur.

Propagation of the vhf/uhf radio waves through the troposphere is greatly influenced by refraction, which is the change of direction, or gradual bending, to which energy waves (radio, light, sound) are subject on passing through a medium of varying density or electrical properties. The refraction of waves passing through air is probably better described by reference to light waves, which are visible, rather than to radio waves which are not.

*"Green Acres", Ibstone, High Wycombe.

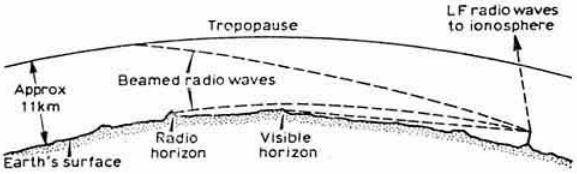

Fig 1. Transmission paths of radio waves

Visual refraction

Mirages are examples of the influence of abnormal refraction in the layers of air close to the earth's surface. They are the result of large vertical temperature gradients which considerably affect the air density in the vertical, and are of two main classes. The most common is the "inferior" mirage which is seen over flat strongly-heated surfaces, eg desert or road surfaces. This mirage produces the illusion of an expanse, or pools, of water. In this case the eye, looking more or less horizontally, sees objects well above the horizon as the light waves are refracted away from the earth's surface (Fig 2), and the apparent expanse of water is really a view of the sky.

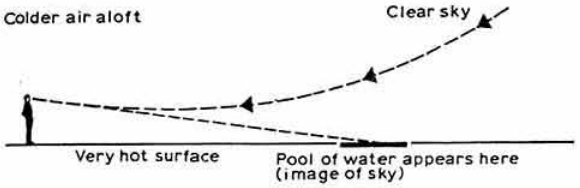

Fig 2. Inferior mirage

The other less common mirage is the "superior" mirage which is seen above a flat surface of much lower temperature than the air above it. The light waves in this case are refracted downwards towards the earth's surface, so that objects which are beyond the normal horizon appear on or even above it (Fig 3).

This "superior" mirage is of considerable importance in vhf/uhf transmissions because it allows one to "see" beyond the normal horizon.

Radio refraction

VHF/UHF radio waves are subject to greater refraction than light waves due to moisture in the atmosphere. Invisible water vapour is always present in the troposphere, and the amount is subject to considerable change, especially near the surface and in the lower troposphere. It varies from one place to another, and from time to time at the same place. The amount of water vapour (or moisture) in the atmosphere is commonly referred to as humidity. The presence of this moisture in the air is of fundamental importance in the study of the anomalous propagation of radio waves because the water molecules become electrically polarized and re-orient themselves as the electric field changes. These charged water molecules considerably enhance the degree of refraction of radio waves.

The degree of refraction is normally measured and expressed by the refractive index (n) of the medium, and is the ratio of the velocity of the wave in a vacuum to its velocity in the medium. The refractive index of air is fractionally greater than 1 and depends on pressure, temperature and humidity; it generally decreases with height so that the rays which pass through the troposphere acquire downward curvature. As the radio refractive index (n) is a quantity only slightly greater than unity (about 1·0003), a fractional percentage change in its value is very important in propagation studies. Very small changes in its value can have a profound effect on the destination of a radio wave.

To simplify calculations it is usual to subtract 1 from the index and multiply the remainder by one million to arrive at N units. Mathematically this is represented as

$$N = 10^6 (n - 1)$$

Under normal atmospheric conditions the refractive index decreases with height, in the lower levels of the troposphere, by about 40 N units/km (3,280ft). This results in normal line-of-sight radio transmissions. When the refractive index decreases with height at a rate of 157 N units/km the radio waves assume a curvature equal to the radius of the earth. Decreases greater than 157 N units/km produce a super-refracting layer in which ducting may occur.

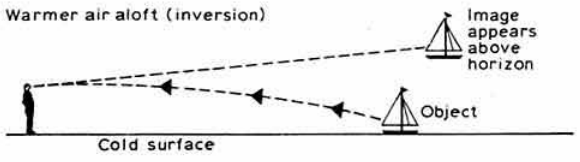

Fig 3. Superior mirage

When ducting occurs the radio waves travel beyond the visible horizon, confined within a shallow layer of air just above the earth's surface—being refracted by the air and reflected by the ground. When this phenomenon occurs it is referred to as "an opening". Whether or not a super-refracting layer leads to ducting depends upon the angle of incidence of the ray and the thickness of the layer. The greater the angle between the ray and the plane of the super-refracting layer, the greater must be the depth of the layer to bend the ray so that it is directed back to the earth's surface. The longer the wavelength the greater the depth of the layer required to allow ducting to take place. The frequency of the phenomenon is, therefore, much greater at the shorter wavelengths.

Normally in the troposphere the temperature decreases with height, but occasionally this state is reversed; that is, the temperature within a shallow layer increases with height. This is referred to as a temperature inversion. The meteorological situation favouring "ducting" or "an opening" is a low level temperature inversion with considerable moisture (or high humidity) below the inversion, and a rapid decrease in moisture above.

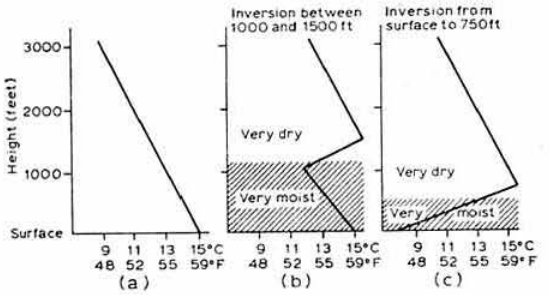

Fig 4. (a) Normal atmospheric condition. (b) Upper layer inversion. (c) Lower level inversion

Fig 4(a) depicts diagramatically the normal atmospheric condition of decreasing temperature with height (moisture not shown). Fig 4(b) depicts an inversion in the layer from 1,000 to 1,500ft, and Fig 4(c) depicts an inversion from the surface up to about 750ft. Both Figs 4(b) and 4(c) indicate situations where ducting is possible. When the air below the inversion is very moist, as indicated by the hatched parts of the diagram, and very dry above, the probability of ducting is greatly enhanced.

Inversions as depicted in Fig 4(b) are often produced in anticyclones (areas of high pressure) where the air in the centre of the high pressure sinks in the lower levels of the troposphere towards the surface. As the air descends towards the surface it is compressed and as a result its temperature rises. (A well-known example of such a heating process is the effect on air in a bicycle pump when it is compressed). A small inversion starts well above the surface and increases in intensity day by day as the air descends slowly to the lower levels—usually to about 2,000ft. Inversions of varying intensity can be found almost always in anticyclones.

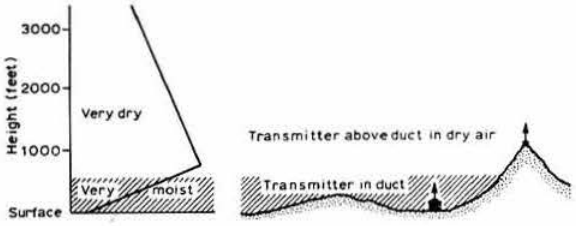

Fig 5. Overnight inversion

Anticyclones quite often move slowly, especially over temperate region land masses in winter where they produce cold but dry weather. During their slow drift across the earth's surface they can produce quite intense inversions (with temperatures increasing with height by about 5°C in a 200ft layer). The very dry air above the inversion (which gives the dry weather) and the moister air below are the preferred conditions required for ducting, and in these situations the ducting may last for several days.

Inversions are also produced when warm dry air moves over colder water. The air is cooled in the lowest layers and at the same time moisture is taken up into this layer from the sea surface. Strong ducts are often produced by this method, especially, for example, when hot air blows off the African continent over the Mediterranean. Such ducts can last for long periods and often persist throughout day and night.

Other inversions which occur over land from ground level to a height of a few hundred feet (as shown in Fig 4(c)), are usually the result of night-time cooling of the land, especially in winter when the nights are long. For these inversions to form there should be little or no cloud during the night and not much wind. The inversion starts to form about sunset, as the earth loses heat into space, and intensifies throughout the night to become most intense about dawn. The cooling of the air near the surface often results in mist, fog, dew or ground frost, all of which are indications of moist air within the inversion layer. As the sun rises, the surface temperature increases—there being little or no cloud—and gradually the inversion is destroyed and the moisture dispersed through the atmosphere, as the mist, fog, dew and ground frost disappear. These inversions, therefore, are normally night-time phenomena which give the best, though temporary, ducting conditions around the dawn period.

In overnight inversions the colder air near the surface tends to sink towards lower ground, so that the most intense of these inversions occur over the lower parts of sloping ground or in valleys. It is possible that vhf/uhf transmitters sited on preferred high ground could be above the inversion, and above the ducting layer, while a lower level transmitter would be within the ducting layer (Fig 5). This situation is less likely to occur with anticyclonic inversions, which are normally at a higher level in the atmosphere.

So far reference has been made to ducting and to the enhanced range of vhf/uhf radio waves, beyond the normal horizon, during these openings. However, it can happen that, when a super-refracting layer exists, interference may occur between two or more transmissions which have traversed slightly different paths. Signals arriving at the receiver at the same time may have left the transmitter at slightly different times, resulting in multipath fading. In the lowest layers of the atmosphere there appear to be many small-scale, short-lived or moving inhomogeneities which give rise not only to fading, but to rapid fluctuations in the fading. So while an opening offers an exciting opportunity to operate beyond one's normal horizon, there are exceptions when, at times, disappointing operating conditions occur due to multipath fading. The same meteorological factors described in this article are at work, but multipath fading indicates that the actual structure of the atmosphere is much more complex than the simple examples considered in this article. □

International beacon project

This project is sponsored and encouraged by IARU Region 1 and organized by Alan Taylor, G3DME. The establishment of the beacon stations has stimulated scientific interest in the propagation paths revealed by reception of the beacons. In addition, they fulfil a practical role by providing signals on what is often otherwise a dead band. With the increase in solar activity during the next few years more of the beacons will become regularly audible in the UK.

Freq (kHz)	Station	Original freq (kHz)	Location	Remarks
28,185	OA4VHF	—	Lima Peru	(1)
28,200	Common	28,200		
28,202·5	9J2BBB	—	Lusaka, Zambia	0500–0600gmt 1500–1600gmt
28,205	DL0IGI	28,195	Mt Predigtstuhl, Germany	QSY 28,200 H+00–05 H+30–35
28,207·5	N4RD	—	Englewood, Fla, USA	
28,210	3B8MS	28,190	Signal Mount, Mauritius	
28,212·5	ZD9GI	—	Gough Island S Atlantic	(2)*
28,215	GB3SX		Crowborough, England	
28,217·5	VK2WI	—	Sydney, Australia	(1)
28,220	5B4CY		Limassol, Cyprus	
28,222·5	YU	—	Yugoslavia	(1)
28,225	VE3TEN	28,175	Ottawa, Canada	
28,227·5	FX3TEN	—	France	(2)
28,230	ZL2MHF	28,170	Mt Climie, New Zealand	
28,232·5	VP8	—	Falkland Is.	(2)
28,235	VP9BA		Southampton, Bermuda	
28,237·5	LA	—	Norway	(1)
28,240	PY1CK	28,160	Rio de Janeiro, Brazil	(3)
28,242·5	ZS	—	South Africa	(1)
28,245	A9XC		Hamala, Bahrain	
28,247·5	EA2OIZ	—	Spain	"Unofficial"
28,250	W	28,150		(1)
28,255	W6	—	Calif USA	(1)
28,260	VK5	—	Australia	(1)
28,265	VK6	—	Australia	(1)
28,270	VK8	—	Australia	(1)

Notes: (1) In planning stage
(2) Under construction (2)* Expected to be operational soon
(3) Being re-built after period of unserviceability